The MESSENGER Orbiter Mission to Mercury

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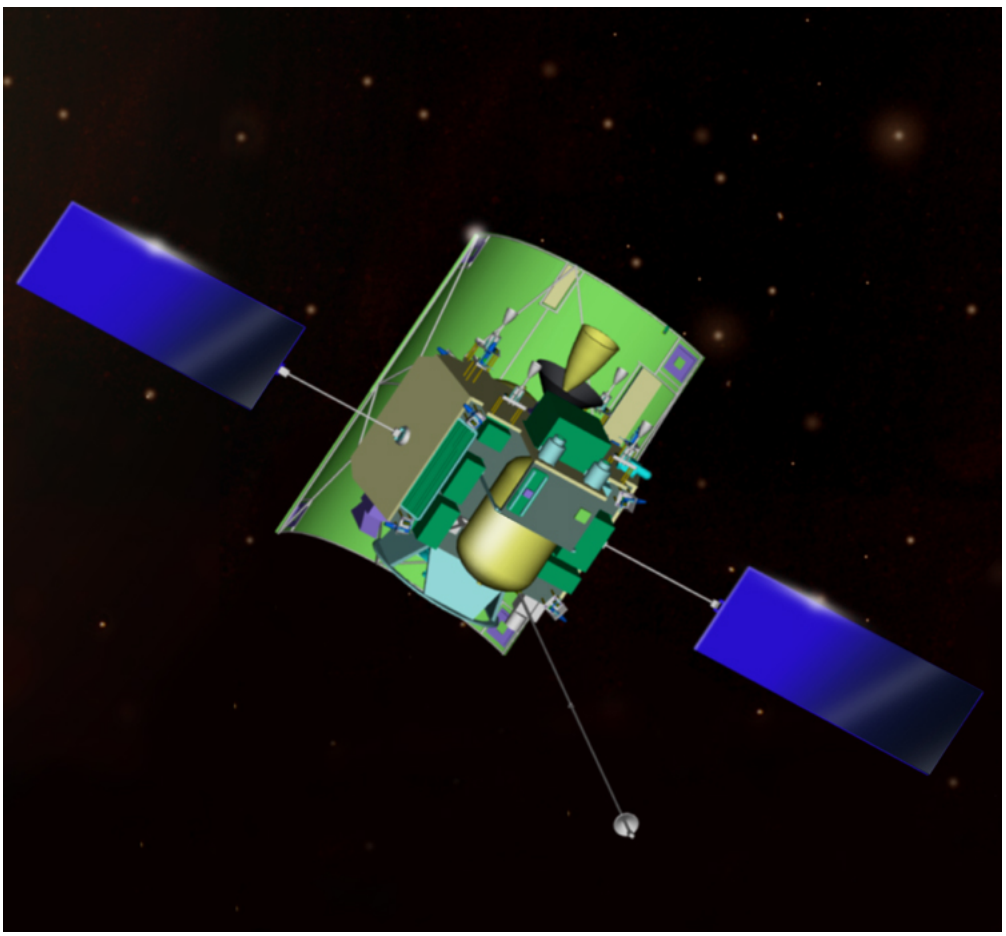
Abstract

MESSENGER is a MErcury Surface, Space ENvironment, GEochemistry and Ranging mission to orbit the planet Mercury for one Earth year following two flybys of that planet and two flybys of Venus. Here we point out the major science questions about Mercury that will be addressed by measurements from seven major instruments on the spacecraft along with the radio tracking. The Science Team for the mission is presented along with each team member's responsibilities showing the wide range of expertise necessary to accomplish the mission objectives. Methods of participation in the mission by members of the scientific community not on the Science Team and not otherwise associated with the mission are indicated.



Introduction

Mercury is one of the most interesting yet least explored planets in the solar system except for Pluto. It is the closest planet to the Sun and is therefore always seen in a twilight sky. The difficulty of observing the planet under these circumstances kept it shrouded in mystery until relatively recently. Its mass had been estimated from the gravitational perturbations of Venus's motion (Ash et al. 1967) and from this we deduced that Mercury has the highest uncompressed density of any body in the solar system (5.3 g/cm^3). The ratio of nickel-iron to silicate type material is the highest of any terrestrial type body. The nickel-iron core of Mercury has a radius of approximately 75% of the planetary radius and the metallic component comprises about 65% of the total mass (Siegfried and Solomon, 1974)---more than twice the ratio for Earth, Venus or Mars.

Because of its proximity to the Sun, it had been long assumed that tidal friction had reduced Mercury's rotation to a rate that is synchronous with its orbital motion–like that of the Moon, and observations of the repetitions of light and dark patterns on the surface seemed to verify this assumption (Dollfus, 1953). It came as quite a surprise then when radar observations revealed Mercury's rotation period relative to the stars to be close to 59 days (Pettengill and Dyce, 1965) instead of the 88 day period of the orbital motion. Theoretical arguments showing that Mercury should be rotating with a period precisely 2/3 of its orbital period, stabilized against further tidal retardation because of its axial asymmetry and the high eccentricity of its orbit (Colombo, 1965; Goldreich and Peale, 1966), were confirmed by subsequent high resolution observations of the topography. Figure 1 pictures Mercury's rotation viewed from above the orbit. This was about the extent of our knowledge of Mercury until 1974.

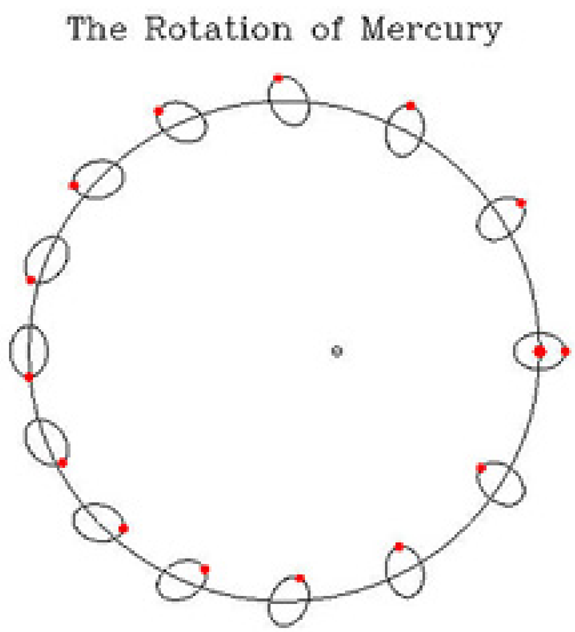


Figure 1
Mercury's rotation in the 3:2 spin-orbit resonance. The ellipses representing Mercury's orientation around the orbit are equally spaced in time.

Most of what is now known (Chapman, 1988; Vilas et al. 1988) comes from the three flybys of Mercury by Mariner 10 in 1974 and 1975. Mariner 10 imaged only about 45% of the surface at an average resolution of about 1 km and less than 1% of the surface at better than 500 m resolution. Further, Mariner 10 discovered the planet's internal magnetic field: measured the ultraviolet signatures of H, He, and O in Mercury's atmosphere; documented the time-variable nature of Mercury's magnetosphere; and determined some of the physical characteristics of the surface including distributions of plains and craters on the imaged parts and the discovery of scarps as long as 500 miles. Subsequent ground based discoveries include the Na and K components of the atmosphere (Potter and Morgan 1985, 1986). It was recognized that a spacecraft orbiting Mercury would greatly supplement this meager knowledge and provide answers to many of the scientific questions that we will discuss below.

But because of Mercury's close proximity to the Sun, it was thought that insertion of such a spacecraft into orbit about the planet could not be done with a conventional propulsion system, a view that drastically decreased the priority of further investigation of the planet. This difficulty in orbit insertion arises because of the high velocity a spacecraft would have relative to Mercury when it arrived from the vicinity of the Earth. For example, an elliptic spacecraft orbit with its aphelion (furthest point from the Sun) at the Earth's distance from the Sun (1 astronomical unit or AU) and its perihelion (closest point to the Sun) at Mercury's aphelion distance at about 0.46 AU is easy to attain and would be a natural trajectory to bring a spacecraft near Mercury. However, the spacecraft would arrive at Mercury with a velocity relative to the Sun of a little more than 51 km/sec and relative to Mercury of more than 12 km/sec. On board rockets would have to reduce the spacecraft velocity (Δv) by almost 9 km/sec for orbit insertion during the very brief time when the spacecraft is close to Mercury. A spacecraft designed to carry the large rocket and the large amount of fuel necessary for such a Δv would result in a prohibitively expensive mission, and it could deliver only a very small payload of instruments into orbit.

But just as encounters of spacecraft with a planet can increase the spacecraft velocity relative to the Sun for gravity assisted trajectories to the far outer solar system, such encounters can reduce the heliocentric spacecraft velocity. A spacecraft can be eased to smaller and smaller heliocentric orbits with a series of such encounters and arrive at Mercury with a slow enough velocity to allow insertion of a sizable payload into orbit *with current launch systems* (Yen, 1985, 1989). The MESSENGER spacecraft will use two gravity assists by Venus and two by Mercury itself before orbit insertion as it flies by Mercury the third time. Of course, one pays for this gradual approach to Mercury with relatively long missions, but we can now orbit Mercury and probe its secrets with unprecedented scrutiny. MESSENGER, launched in March 2004, will enter Mercury orbit in September 2009 and carry out comprehensive measurements for one Earth year. The orbit chosen to maximize the science return while minimizing the effects of the severe thermal environment for the MESSENGER spacecraft about Mercury is a polar orbit with a reasonably large eccentricity.

Science motivation for the MESSENGER mission

MESSENGER is focused on answering the following key scientific questions, which are motivated by and comprise natural extensions of our current knowledge. Together, answers to these questions will substantially increase our understanding of how terrestrial planets formed and evolved.

1. What planetary formation processes led to the high metal/silicate ratio in Mercury?

2. What is the geological history of Mercury?

3. What is the nature and origin of Mercury's magnetic field?

4. What is the structure and state of Mercury's core?

5. What are the radar reflective materials at Mercury's poles?

6. What are the important volatile species and their sources and sinks on and near Mercury?

A global map of the surface composition and mineralogy will distinguish between the hypotheses for Mercury's high density in question 1 and thereby tell us which of several processes dominated during the formation of the terrestrial planets. The various processes during the formation stage predict different compositions of the surface. The global elemental abundances on Mercury's surface will be determined by the X-ray (XRS) and the γ-ray and neutron spectrometers (GRNS). Atoms in the top few mm of the surface have deep electronic levels vacated by solar X-rays, and subsequent decay back to the electronic ground state identifies the element with characteristic line emission. Energetic galactic cosmic rays excite nuclei in the top few cm of the surface, and decay back to the nuclear ground state with characteristic γ-ray line emission identifies the nucleus. Neutrons are also generated by cosmic ray collisions with surface elemental nuclei and slowed down by collisions with low mass elements such as hydrogen. They are also absorbed and scattered by other nuclei as they progress toward leakage from the surface above which they can be detected. The neutron spectrometer will be most useful in identifying the volatile content of the polar deposits discussed below. These elemental distributions will be supplemented by constraints on the distributions of minerals from the Visible and Infrared Spectrometer (VIRS) part of the Atmosphere and Surface Composition Spectrometer (ASCS) and the set of instruments will provide a self consistent determination of the surface composition and its variation over the surface.

The geological history of Mercury sought in question 2 is crucial to understanding how terrestrial planet evolution depends on planet size and initial conditions. The geological history developed from Mariner 10 images (Strom, 1979, 1997; Spudis and Guest, 1988) is uncertain because of the limited coverage and resolution. For example, volcanic lava flow fronts, such as those seen on the Moon, would not be visible at the Mariner 10 resolution. The geological history of Mercury will be deduced from the global imaging coverage at 250 m/pixel with the Mercury Dual Imaging System (MDIS), including stereo geometries supplemented with precise elevations from the Mercury Laser Altimeter (MLA). The goal is to understand the sequence of tectonic deformation, volcanism and cratering that shaped Mercury's surface. The distribution of the surface composition and mineralogy from the XRS, GRNS, and ASCS will constrain the interpretations of the geological sequences. The thermal history of the planet is also correlated with its geologic history. The strong temperature dependence of elastic and ductile strengths of rocky materials allows constraints to be placed on temperature gradients near the surface by comparing the gravitational field variations obtained from the radio tracking of the spacecraft with the topography obtained with the MLA. The ubiquitous lobate scarps seen by Mariner 10 are likely indications of thrust faults on a cooling and thereby shrinking planet.

Question 3 will be addressed by the magnetometer (MAG) and the Energetic Particle and Plasma Spectrometer (EPPS). MAG will map the configuration and time variability of the magnetic field, while the EPPS determination of the distribution of types, abundances, energetics and dynamical characteristics of the ions will help distinguish what part of the local field is internally generated in Mercury and what part is derived from external sources. This combination of measurements will distinguish Mercury's field from that carried by the solar wind. The true field configuration will constrain the nature of its source. Is the field really due to dynamo action in a liquid outer core?

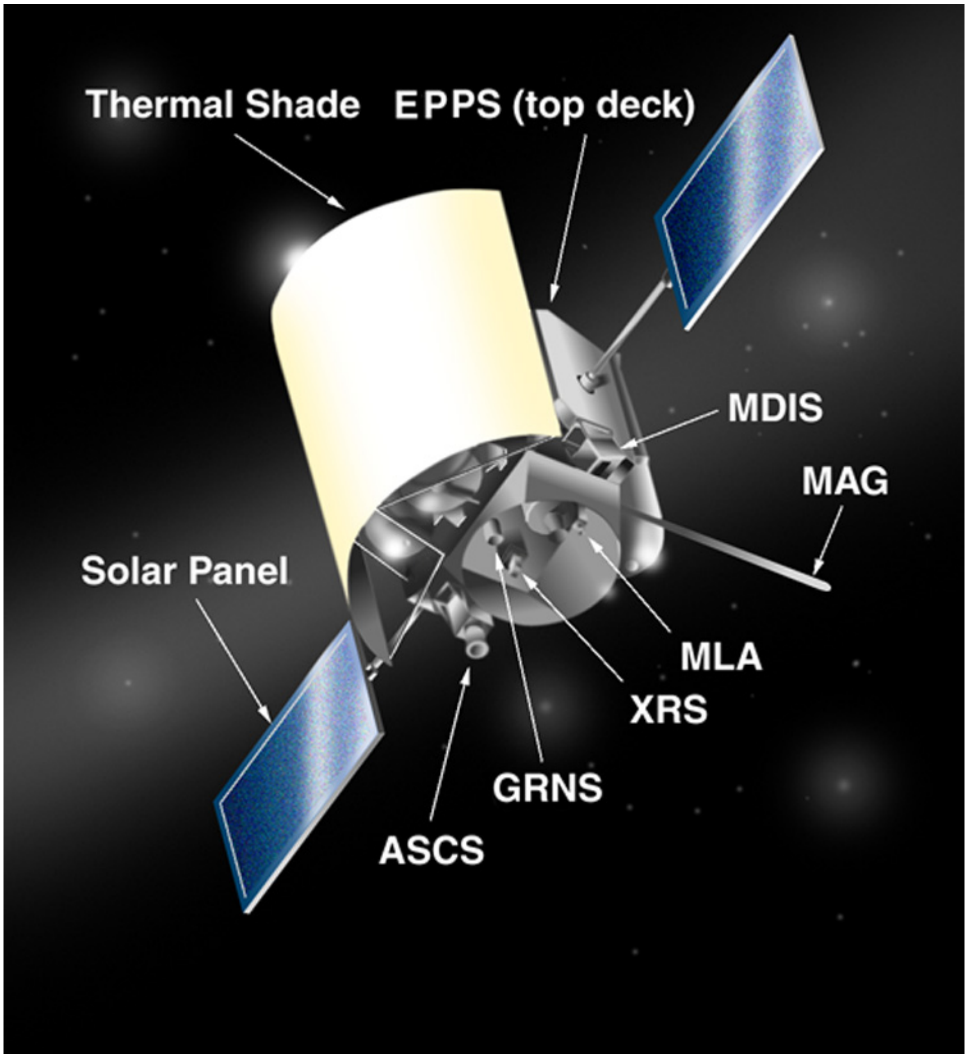


Figure 2
The MESSENGER spacecraft with Sun shield, solar arrays and seven instruments.

This last question is a prime motivation for question 4, which will be addressed by measuring the amplitude of the physical libration with the laser altimeter and radio tracking experiments. A metallic liquid outer core is necessary for a dynamo to work, but there is justified concern that such a liquid Ni-Fe core would have solidified over the age of the solar system in such a small planet (Siegfried and Solomon, 1974) unless sustained with a lower melting temperature by a sufficient contamination of another element such as sulfur (Schubert et al. 1988). The nature of the core is distinguished by the fact that the amplitude of the physical libration will be about twice as large as the solid planet value if the mantle is decoupled from the interior by a liquid layer. This libration is a periodic variation in Mercury's rotation rate around the mean spin angular velocity of 1.5 times the mean orbital angular velocity. It is induced from the gravitational torques on the non-axisymmetric shape of Mercury as it rotates relative to the Sun. Figure 1 shows the variation in Mercury's orientation around the orbit, where the solar gravitational torque always tries to align the long axis of Mercury with the Mercury-Sun line. In addition to the physical libration amplitude, the obliquity (angle between the equator and orbit planes) and the lowest order coefficients in the spherical harmonic expansion of Mercury's magnetic field, C_{20} and C_{22} must be determined (Peale, 1976, 1981, 1988, 1997). The first will be found along with the libration amplitude from the laser altimetry and radio science and the latter two numbers are part of the overall gravitational field determination from precise radio tracking of the spacecraft.

Question 5 is motivated by radar images that show regions of high radar reflectivity at the poles (Slade, et al., 1992; Harmon and Slade, 1992). These bright regions return a radio wave dominantly polarized in the same sense as that sent, whereas solid objects such as the Moon return mostly the opposite polarization. The anomalous polarization is a signature of relatively deep and clean water ice. The circular polarization of the radar wave can be thought of as an electric vector perpendicular to the direction of propagation that rotates uniformly while advancing down the direction of propagation at the speed of light. The tip of the vector thereby describes a spiral along the propagation path. Normally most of the wave energy reflects from a solid body as in a mirror, such that the returning wave has mostly the opposite polarization. I.e., the observer sees the electric vector in the returning wave rotating the same direction as that in the wave he sent, but the wave is now propagating toward him instead of away, so the polarization is reversed. The Moon and the equatorial regions of Mars and Venus all demonstrate the dominance of the opposite polarization in the reflected radar waves.

It came somewhat as a surprise that the radar reflections from the icy satellites of Jupiter and from the ice caps of Mars came back with most of the radiation polarized in the *same* sense as that propagated (Ostro et al., 1988). This was explained by the realization that most of the radar energy is not reflected or absorbed at the surface of the ice as it was for rocky objects, but that it passed into the ice and was internally scattered off of inhomogeneities (buried craters?) to emerge from the interior with same polarization with which it entered---much like the reflection from a corner cube (Eshleman, 1986). The ice had to be deep relative to the wave length of the radar beam and not be very absorbing. Since the bright radar regions at Mercury's poles had the same anomalous polarization signature as the ice caps of Mars and as the icy Galilean satellites, water ice would seem to be in the dark shadows at Mercury's poles. A lower absolute radar reflectance than the Martian polar cap can be the result of incomplete areal coverage by ice units or a thin cover of dust or soil (Butler et al., 1993).

The permanently shadowed floors of impact craters near the poles are sufficiently cold (~60K) to preserve water ice for billions of years, assuming that Mercury has had its currently small obliquity for such a time (Paige et al., 1992; Ingersoll et al., 1992; Butler et al., 1993). Indeed, many of the areas of highest backscatter coincide with known impact structures imaged by Mariner 10 (Harmon et al., 1994). The source of the water ice is not known. It could be internally generated, or due to impact volatilization of cometary and meteoritic material followed by random-walk transport to the poles.

Sprague et al. (1995) proposed an alternative hypothesis that the polar deposits are composed of elemental sulfur, which can also be considered a volatile which could reach the cold traps at the poles in a manner similar to the transport of water vapor. A natural source of the sulfur vapors would be volcanic outgassing much as in terrestrial volcanos.

The GRNS will determine if Mercury's polar deposits contain hydrogen in water ice or sulfur. The neutron spectral signature of the hydrogen in water ice is unique, and that of sulfur will be compelling although not unique (Feldman et al., 1997). Coupling the neutron measurements with gamma ray spectra and UV spectral analysis of the volatile effluents will identify the volatiles comprising the polar deposits. Collisions of cosmic-ray-generated neutrons with hydrogen nuclei (protons) cause the neutrons to lose their initially high energies rapidly. This “moderation” of neutrons is often accomplished in nuclear reactors by surrounding the fuel rods with water. Neutrons lose energy slowly during scattering from heavy nuclei. This difference in the moderation properties of different polar deposits along with differences in the scattering and absorption cross sections of neutrons for various nuclei lead to the different energy distributions of those neutrons that leak from the surface. In addition, some of the neutrons will combine with protons to make deuterium with the emission of a γ-ray at 2.23 Mev. This will be seen by the gamma ray spectrometer if there is a lot of hydrogen (*i.e.*, water ice) in the deposits. Finally, the particle and plasma (EPPS) and UV (the Ultra Violet and Visual spectrometer (UVVS)) part of ASCS) spectrometers will identify the effluent from the frozen volatiles.

The ASCS/UVVS will address the sixth question concerning the volatile species in the atmosphere. The UV spectrometer will measure the composition, structure and time variability of Mercury's tenuous atmosphere. Correlations of the time variability with solar time, solar activity and the planet's distance from the Sun will constrain mechanisms of volatile release from the surface or volatile injection from the solar wind. Conjectures about the surface composition predict many more species in the atmosphere than the H, He, O, Na and K that have already been detected, and the spatial distribution of these species will be correlated with the distribution of surface composition and mineralogy thereby identifying the local source of the detected atmospheric species. The energetic particle part of EPPS will measure the exchange of species between the atmosphere and magnetosphere, and the plasma spectrometer part will identify and quantify those ions picked up by the solar wind. All of these measurements will be combined to identify the sources and sinks of the volatile species and the dynamics of their transport. We have already seen how this works in the identification of the volatile species in the polar deposits.

A great virtue of the MESSENGER mission is the way the instrumentation has been chosen to address all of the major science questions we have assembled about Mercury in a way that provides great redundancy and tests for self consistency. The cross correlations of the measurements will effectively constrain the answers to the major scientific questions. At the same time, we expect that many more, completely unanticipated puzzles will be disclosed such as happened during the spacecraft Galileo's scrutiny of the Jovian system. Figure 2 shows the spacecraft with its Sun shield and the instruments discussed above.

The Science Team

The variety of disciplines involved in understanding Mercury's current state, its history, the constraints it places on the theory of origin of the solar system and the variety of technologies employed in the measurements required the assembly of a science team with a range of expertise sufficiently wide to span these disciplines. The science team is shown in Table 1 along with their responsibilities during the mission development and execution and in interpreting the data that is returned.

Mission Implementation

To implement the mission, the Principal Investigator, Dr. Sean C. Solomon, Director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington (CIW), and The Johns Hopkins University Applied Physics Laboratory (JHU/APL) head a consortium of companies and universities to provide the spacecraft and instrumentation. The Applied Physics Laboratory is an organization with an unusually competent and experienced set of engineers and scientists. Their attention to detail and their management skills have produced a long series of successes associated with NASA missions. A recent example is their construction of the Near Earth Asteroid Rendezvous (NEAR) spacecraft which was delivered on time and under budget. Their NEAR mission management has continued successfully as the spacecraft nears orbit insertion about the asteroid Eros on Feb. 14, 2000. MESSENGER is in good hands.

To engage students and the public, the MESSENGER Education and Public Outreach (E/PO) Plan is coordinated by the American Association for the Advancement of Science. The extent and completeness of the E/PO Plan is indicated by the following partners in this undertaking: Messenger Science Team, Challenger Center for Space Science Education, Carnegie Academy for Science Education, Proxemy Research, Inc., Montana State University Center for Educational Resources (CERES), National Air and Space Museum, American Museum of Natural History, Minority University-Space Interdisciplinary Network (MU-SPIN), Space Explorers, Inc., Independent documentary film makers. Activities will include educational efforts at all pre-college levels, provision of curriculum support materials, student internships to work with science team members, teacher workshops and internet based courses. The disadvantaged public will be specifically sought out to receive MESSENGER information. Two major documentaries will be be developed along with a series of programs during the mission. Minute radio segments will inform the public during the mission and materials for the media will be provided. Museum displays will be assembled and two general audience books will be put together. These activities will carry the excitement of the MESSENGER mission to students, teachers and the public perhaps more so than any previous NASA mission.

The returned data

Unlike many previous missions to the planets, there is no proprietary period of exclusive use of the Mercury data by the scientific personnel associated with the mission. The MESSENGER team is committed to providing all mission data to the scientific community as soon as processing and validation are completed. All validated mission data will be archived with the Planetary Data System (PDS). In parallel with this archiving, scientific results will be shared with the science community via scientific meetings and peer-reviewed publications. Public dissemination of images and data will start immediately following their receipt. Additional data products of scientific interest will be disseminated in electronic and printed formats. Optimal use will be made of the World Wide Web to provide results to the scientific community, to mission educational and outreach endeavors, and to the general public.

Given that the data will be available as received, scientific personnel outside the mission can use the data for their own analysis, and they can seek support for this analysis by submitting proposals to the appropriate discipline (e.g. Planetary Geology and Geophysics) in the NASA Research and Analysis Program or to similarly appropriate disciplines in NSF.

Table 1. The MESSENGER science team

Team Member	**Role and Responsibility**
Sean C. Solomon	Principle Investigator. Leads MESSENGER effort with responsibility for design, execution, and success of the mission, reports on project progress and status to NASA. Co-chairs all Science Team meetings. Ex-officio member of each Science Team group. Leads overall scientific analysis effort and participates in interpretation of imaging geochemical and geophysical measurements.
Mario H. Acuña	Shares in development of MAG. Participates in the analysis of magnetometer data.
Daniel N. Baker	Participates in the analysis of MAG, EPPS and UVVS data. Leads efforts to characterize magnetospheric processes.
William V. Boynton	Participates in the development of GRNS and XRS. Leads the analysis of γ-ray, neutron and X-ray measurements.
Clark R. Chapman	Participates in the analysis of imaging and IR spectral measurements. Leads interpretation of the impact cratering

	record.
Andrew F. Cheng	Leads the analysis of MAG, EPPS, and UVVS data for the study of interaction of the magnetosphere and the planetary surface.
George Gloeckler	Oversees development of Plasma Spectrometer subsystem of EPPS. Leads the interpretation of thermal plasma data.
Robert E. Gold	Implements science payload. Oversees the development of EPPS. Participates in analysis of energetic particle data.
James W. Head III	Leads the analysis of imaging data for the identification of volcanic features and the stratigraphic analysis of geologic units.
Stamatios M. Krimigis	Leads the analysis of EPPS data to characterize the magnetosphere and interplanetary medium.
William McClintock	Oversees development of ASCS. Leads the interpretation of UV spectra. Participates in the interpretation of IR spectra.
Ralph L. McNutt, Jr.	Project Scientist: assists PI. Oversees development of GRNS and XRS. Participates in analysis of surface composition.
Scott L. Murchie	Oversees MDIS development. Leads development of observing sequences and interpretation of imaging and spectral data.
Stanton J. Peale	Leads strategy for and interpretation of measurements of planetary orientation and physical liberation.
Roger J. Phillips	Leads the analysis of topography and gravity data for regional tectonics and interior dynamics.
Mark S. Robinson	Leads development of mosaicking and geometrical corrections for MDIS. Leads the analysis of imaging and spectral data.
James A. Slavin	Participates in development of MAG. Leads the analysis of magnetometer data for magnetic field structure.
David E. Smith	Participates in analysis of imaging and IR spectral measurements. Leads investigation of radio science. Participates in analysis of MLA data.
Robert G. Strom	Participates in analysis of imaging and IR spectral measurements. Leads the interpretation of volcanic and tectonic history.
Jacob I. Trombka	Oversees selection of GRNS and XRS detectors. Participates in the analysis of γ-ray, neutron, and X-ray measurements.
Maria T. Zubor	Leads analysis of MLA data. Participates in the analysis of occultation, radio science and gravity/topography data.

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